EUROPEAN GEOTHERMAL DRILLING EXPERIENCE-PROBLEM AREAS AND CASE STUDIES

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ABSTRACT

Geothermal drilling has long been restricted in Western Europe to the sole dry steam field of Larderello in Italy. In the last few years, a wider experience is building up as a consequence of intensified exploration and development programs carried out for evaluation and production of both low- and high-enthalpy geothermal resources. A sample of some 40 boreholes indicates the following problem areas.

1. Low-Enthalpy Drilling

Due to similar settings--hot water system flowing in sedimentary units at temperatures and depths ranging from 40° to 140°C (104° to 284°F) and from 1,000 to 3,500 metres (3,281 to 11,484 feet), respectively--the technology here is strongly dependent on oil and gas drilling practice. Still, specific problems remain in the areas of multiple-reservoir reconnaissance and well completion at production and reinjection levels, particularly in poorly consolidated fluvio-deltaic sequences leading to sand control and swelling clay problems. Expertise needs to be developed to minimize costs, secure high production capacities, long lifetimes, and minimum maintenance compatible with the economics and the lack of suitable workover facilities.

2. High-Enthalpy Drilling

Exploratory drilling is currently combining wildcatting and deeper investigations of known fields. Lost circulation, drill string corrosion, tubulars, mud, cementing, and deviation control are the most frequently encountered difficulties while drilling in hostile water-dominated environments. Formation temperatures in excess of 300°C (572°F) are often the rule, and recent drilling conducted in volcanic areas have hit fluids approaching supercritical state. Whenever these problems do not remain under control, they result in rig standby and extra costs which severely penalize an industry which needs sharp improvements to be fully reliable and cost effective.

Geothermal well stimulation is therefore a field of growing interest, but it lacks adequate procedures.

Current geothermal drilling practice in Europe is illustrated by three typical case studies.

DISCLAIMER

INTRODUCTION

Prior to 1974 geothermal energy (GE) was more or less regarded by European (EC) States an exotic curiosity of marginal impact although, not mentioning Roman ages, at least two countries had long been involved in geothermal matters - Italy in power generation from dry steam sources (Larderello, 1904) and France in direct use of low enthalpy aquifers (Melun l'Almont district heating doublet, 1969).

In the 1960's ENEL, the italian power agency, who had built up its drilling and production experience on the Larderello field, extended exploration to other areas of Tuscany and Northern Latium. This led to the discovery of the Travale and Monte Amiata dry steam and the Cesano pressurized water systems.

Since then, and as a consequence of the energy price crisis, EC countries revisited GE and a pronounced involvement could be noticed. In particular a R & D programme in GE, common to nine member States[a], was launched in 1975 by the Commission of the European Communities (CEC) adressing all aspects of geothermal research, from exploration to production, in which wildcatting took an important part (8).

In spite of a very recent activity in drilling for low grade heat and in active volcanic areas, the european geothermal well record is not negligible as shown in Table 1. It provides already a suitable data base for reviewing major problem areas, associated with exploration and production drilling, with respect to (i) drilling and completion technology, (ii) environmental constraints and (iii) economics.

For the sake of simplification, drilling is divided according to the enthalpy of the geothermal fluid, as drilling of high and low enthalpy wells adresses in fact contrasted geological and thermal environments and different usage and economics.

Three case studies, selected among deep exploration projects supported by the CEC, will illustrate the practical problems encountered in geothermal drilling.

GEOTHERMAL ENVIRONMENTS

The geological structure of Europe and consequently its geothermal environments are commanded by the geodynamic evolution of the Eurasian Plate. It displays a variety of geodynamic settings, most plate tectonic attributes being present except the oceanic crust. Western Europe at large is an area of old and rigid continental crust characterized by crystalline massifs, intracratonic and foredeep basins and continental rifting. A younger crust stretches over the Mediterranean area, where the African and Eurasian Plates collide, exhibiting typical features - subduction, marginal basins, island arcs and extensional horst and graben systems.

[a]Belgium, Denmark, Federal Republic of Germany, France, Ireland, Italy, Luxembourg, The Netherlands, United Kingdom. Greece will join the EC in 1981.

These environments are irregularly distributed though. An important consequence is that the majority of EC States are faced with the sole low enthalpy outlook, high enthalpy sources being limited to Central and Southern Italy and to Eastern Greece.

Fig. 1 displays, at a broad scale, the EC geothermal resource status with indication of the areas where a commercial development can be reliably envisaged. Three main systems can be characterized, respectively :

- low enthalpy resources which prove to be prolific and dependable in foredeep and intracratonic basins wherever they develop regional aquifer units. Such large sedimentary multi-aquifer systems are found in France (Aquitaine and Paris Basins), Italy (Po Valley), United Kingdom (Wessex, East Yorkshire and Northern Ireland Basins), Germany (Southern Molassic Alpine foredeep and Northern Munsterland), Holland and Denmark.

- continental rifting and central, recent but extinct volcanism which stand half way between high and low enthalpy resources. Here, an association of often high temperatures (100 to 160°C) and of complex reservoir and heat source conditions renders exploration delicate. Rift valleys (Limagne, Rhone Valley and Rhine Graben) exhibit intense compartmenting requiring sophisticated seismics, structural analysis and tectonics as to identification of active faulting and porosity patterns.

- high enthaly reservoirs placed along the mediterranean belt, chiefly the Tuscanian distensive tectonic system, the Northern Latium and Campanian plio-quaternary volcanism and the subduction magmatism of the Eolian Arc.

DRILLING DATA BASE

Over 800 wells have been drilled in Western Europe for geothermal purposes, since the early 1900's, with a success ratio of 56 % close to the world average. Note, in Table 1, that for the Larderello field the success ratio is decreasing in the past four years with increasing drilling depths. Low enthalpy drilling, which often consists of drilling a well pair, the so called geothermal doublet, for conservative and environmental reasons is still in its early development stage. Future developments - about 400 wells scheduled in the next five years, should the rig and manpower be available - should markedly improve this ratio. Two areas of the EC are already, or likely to be, intensely drilled. One is the Larderello field with the high well concentration depicted in Fig. 2. It is obvious that effective well stimulation techniques would significantly improve the economics of the exploitation of this fracture dominated field. The second is the Paris outskirts, shown in Fig. 3, where some 60 planned doublets emphasize drilling, work over and related environmental implications in urban areas.

LOW ENTHALPY DRILLING

Most of the oil and gas drilling background is transferable to hot water drilling which requires a similar technology owing to a similar environment - aquifers flowing in sedimentary rocks at depths and temperatures varying from 40 to 140°C and 1000 to 3500 m respectively. Still, there are a few striking differences in the areas of well completion, reconnaisance, drilling fluids, environmental constraints and, of course, economics.

Basically, low grade heat being of low market value is not yet transportable economically over distances greater than 5 km. Drilling costs, elsewhere, are high (see Table 2) - twice the North American figures - because of a shortage of inland rigs and of the competition with hydrocarbon exploration programmes. In 1981, a cost of 2 million US $ for a 2000 m deep well tends to become the rule all over western Europe. As a result (i) high well productive capacities, say 100 m3/h or 15,000 bbl/d for a commercial hole by 1980 standards are required to ensure a decent return on investment; which (ii) implies significant heat loads in the vicinity of the well source - tenths of thousands Gcal/year - which (iii) bounds development to district heating of large cities.

Well Completion

A major difficulty in geothermal energy is the adequate cementing of columns including liner hangers, a problem with which one has to live.

Most carbonate geothermal reservoirs are produced (and injected) in open hole - Dogger in the Paris Basin, carboniferous karstified limestone in Belgium and createceous dolomite in Aquitaine - and exhibit, due to their fracture dominated porosities, high yields.

Triassic clastic deposits (sandstone and interbedded clay) are less dependable reservoirs because of random porosity trends (compaction, diagenesis) and require suitable well completion. The rule, below 1500 m, is to avoid the placement of a gravel pack which is considered a too risky operation. A good substitute, already experienced in underground gas storage, is to set down hole wire wrapped screens of either oil and gas or superweld type (   ). A classical design would be a Ø 6" 5/8 stainless 316L superweld screen, with a 0.8 mm slot, on a well producing from a sand and sandstone matrix. No sand control problems have yet appeared.

Reinjected fluids being cooled formation fluids, circulated under pressure, fluid compatibility, swelling clay and precipitation problems are minimum to date.

Multi Aquifer Reconnaissance

In the center of the Paris Basin coexist the possibility of producing either the Dogger or the Trias reservoirs. The Dogger is a reliable open hole producer but is cooler whereas the Trias is hotter but random as to porosities and moreover it requires a completion. Only direct assessment by testing can optimize this balance. There are three possible strategies :

i.	Target reservoir : Trias	Produced reservoir : Trias
ii.	Target reservoir : Dogger	Produced reservoir : Dogger
iii.	Target reservoir : Trias	Produced reservoir : Dogger

i and ii pose no problem. In case situation iii was encountered the design depicted in Fig. 4 has been suggested and agreed on.

It consists, in brief, of the following sequence :

- Well drilled to the basement, TD : 2000 m (vertical)
- Testing of the Dogger
- No cementing of the Ø 9" 5/8 casing in the Dogger in order to produce it should the Trias exhibit poor reservoir performance. To prevent casing corrosion by Dogger brines a thixotropic gel ("Ken Flow") is placed by means of a DV stage cementer.
- Testing of the Trias
- Plugging the hole by a cement plug set below the Dogger.
- Opening of the Dogger window either by perforating the Ø 7" liner or by milling and extracting after pulling out the liner hanger.
- Production of the Dogger by releasing the "Ken Flow" through perforations or the Ø 8" 1/2 open hole after pulling out the Ø 7" liner.
- The Ø 9" 5/8 becomes the reinjection column.
- Drilling of the production borehole, objective Dogger.

Caving and stuck drill pipe

In the Paris Basin (see a typical geological log in Fig. 5) a major drilling problem arises when crossing the Kimmeridgian. This formation, some 150 m thick, composed of alternating carbonate and clay streaks causes, if drilling parameters are not perfectly adjusted, caving and subsequent sticking. This proves cumbersome, particularily in slant drilling required by geothermal doublets. It soon appeared that light muds with low solid content were the solution. Therefore, oil based muds were substituted to the routinely used bentonitic muds. Fig. 6 clearly shows the improvement brought by oil based muds on borehole geometry. Adequate mud cleaning facilities at surface keep environmental problems to a minimum (less than 3 % oil content in cuttings).

Oil Based Muds

In general, reluctance is frequently noticed among professionals towards using oil base muds despite their many advantages, principally because of environmental (disposal and fire) and economical considerations.

In one case use of these muds is reported satisfactory (9) during most of the drilling sequence. The site constraints were such - urban area, little available space, target formation distant from the drilling platform - that it was necessary to drill in a Ø 8" 1/2 diameter at a 40° drift angle with light muds (density of 1.04 - 1.05), no reserve pit and no pollution of the environment.

Oil based muds were found to best meet these objectives by their ability to (i) secure fast drilling rates by minimizing friction and sticking risks associated with slant drilling, (ii) limit formation damage and (iii) avoid hydration of marls and related swelling and caving problems.

The implications were threefold, (i) to keep density under control by avoiding discharge, (ii) to limit mud losses when removing solids and (iii) to reduce significantly treated and waste volumes. This emphasizes solid treatment. A rather standard mud cleaning device was added to the mud circuit sketched in Fig. 7.

It enabled to remove 54 % of the solids and to recover 89 % of the emulsion of the desilter heavy effluents. Drilling could be completed in 20 days from 200 to 1330 m with less than 5 % redrilling time, and below the projected budget. Density was always kept at 1.05, with a total mud volume of 200 m3 and a percentage of removable drilled solids equal to 67 %. Moreover no pollution is reported.

Noise

Conventional, non electric, petroleum rigs used in geothermal drilling can generate noise up to 85 dbA whereas legal environmental regulations set the limits in urban areas, with heavy traffic, to 45 + 15 = 60 dbA and 45 + 5 = 50 dbA during day and night time. Excess noise margins are of 5 and 3 dbA respectively.

Waiting for electricity driven rigs, temporary measures can achieve the objective of drilling at tolerable noise levels. They consist, among others, of :

- suppressing generator sets, replaced by connections to the grid,
- orienting the drilling platform and noisy engines according to the direction of dominant winds,
- setting mufflers and hoods on engines,
- building anti-noise walls, batters or wooden screens,
- avoiding noisy operations at night : stem manoeuvers, cementing, logging.

They result in additional costs estimated at 100,000 US $.

Oil and gas drilling practice versus geothermal reservoir evaluation

The following case study (6) may well illustrate the problems likely to be encountered when applying straight forward petroleum routine to geothermal exploration.

Type of well : wildcat.

Objective : evaluation of hot water bearing formations inferred in Triassic fluvio continental deposits; reservoir rocks = sand, sandstone, interbedded clay.

Predicted down hole characteristics : TD = 3000 m, BHT = 130-150°C, pressure = hydrostatic.

Location : populated suburban district, optimized by a vibroseismic survey.

Regional background knowledge : previous hydrocarbon exploration and production drillings, some 20 km apart, and playback of a continuous seismic coverage enable the geology of post-Triassic terrains to be reliably assessed.

Technical column : Ø 13" 3/8 casing (1200 m), Ø 9" 5/8 liner (1100-1900 m), Ø 7" liner (1800-2600 m) - Reservoir ; either open hole, wire wrapped screen (Ø 4" 1/2) or slotted liner (Ø 4" 1/2).

Mud programme : bentonitic, bentonitic + lignosulfonate and baryte, saturated brine.

The outcome was the following :

Predicted and actual figures stand in rather close agreement as to TD (3200 m), temperature (140°C) and formation pressure. Reservoir top is hit at 2700 m and a net pay of 150 m is assessed from the CNL-BHC porosity cross plot (cut-off porosity : 8 %).

Major events : incomplete cementing of the 13" 3/8 - 9" 5/8 liner hanger. At 2000 m a mini eruption of oil and dissolved gas is controlled by the crew. It causes a strenghtening of safety regulations : well head change and anti-explosive modifications brought to the rig. Drilling resumes with a bentonite lignosulfonate mud of density 1.13 at reservoir top (1.08 for hole control and cutting recovery, 0.05 for 5 bars/1000 m over pressure control). Total lost circulation at 2850 m. Mud losses : 185 m3. After control, drilling progresses to TD with a bentonitic mud (d : 1.03 - 1.04). Mud losses : 290 m3. An acid frac job is performed and a 600 m Ø 4" 1/2 slotted liner set down hole before move-out. Number of cores : three (top - reservoir - basement). Number of casing DST's : 3 (first : dry, second : productive; third over total open hole section : less productive).

Diagnostic : reservoir plugged by a bentonic mud in a hot (140°C) aquifer environment; unsufficient reservoir reconnaissance; no further reservoir investigations possible (flowmeter, side wall coring) owing to a nonremovable slotted liner. Failure reasons are three fold : blow out fears, inadequate mud, budget limitations. The first caused denser drilling fluids and exaggerated hole control, the second resulted in formation damage, the third in a funnel shaped column, the cheapest mud formula and too fast drilling rates at reservoir level.

Consequences : side track from reservoir top, with saltwater as a drilling fluid and a modified hole geometry (7" casing tied back to the former 7" - 9" 5/8 liner hanger). Subseqüent extra costs are estimated at 1.2 million US $.

HIGH ENTHALPY DRILLING

General

For many years high enthalpy drilling was bound to Tuscan dry steam fields and it is only recently that more diversified settings have entered the geothermal drilling and production picture. Of the 814 wells drilled at temperatures above 150°C about 30, drilled in the past decade, dealt with water dominated systems. Relevant environments can exhibit formation temperatures in excess of 400°C and a bottom hole temperature of 300°C is a quite common figure. CO_2 contents as high as 80 % are sometimes noticed in the early producing stage (Torre Alfina). Reservoir rocks include : quartzite, phyllite and anhydrite (Larderello, Travale, Monte Amiata, Pian Castagnaio) - Carbonate (limestone and dolomite) rocks (Larderello, Travale, Torre Alfina, Cesano, Latera) - alkaline tuffaceous products (Mofete, San Vito) - micaschists, crystalline and metamorphic rocks (Milos). But in general it is less the nature of the rock than its fractured porosity, the dominant feature of geothermal reservoirs, which is a problem. Hard and abrasive rocks are drilled at decent rates with conventional tools. Lengths of 75, 100 and even 125 m drilled with the same tool are not uncommon in geothermal bit records. It is more a matter of tool to formation adequacy than of adequate tool availability.

Fractures, especially when massive as in the Larderello field, associated with high temperatures cause the major problems as to lost circulation control, cementing jobs and setting of multiple casings. These difficulties are the major reasons to the twofold increase of geothermal drilling costs as compared to equivalent oil and gas operations. Statistics, carried out on a sample of 20 wells drilled at depths of 1000 to 1500 m with similar technologies show (Munier Jolain, personal communication, 1980), for hydrocarbon versus geothermal : total duration (days) 30/50, effective drilling time (%) 35/20, tool lifetime identical, control (losses, cementing...) and instrumentation (%) 13/30.

Although lost circulations are not to be overlooked (see example further) they are usually kept under control by cement plugs - up to 17 are reported on a job at 120 m depth. So cementing is the major puzzle especially when considering that squeeze and stage cementing are ruled out in geothermal wells. A rule frequently adopted consists of placing three successive columns (17" 1/2 - 13" 3/8 - 9" 5/8 - 7") continuously, cemented but not necessarily over the entire length, with expansion spools at well head. Slotted liners are more a makeshift than a need. A standard cement utilized in the EC is the Italcementi Geotherm Class G cement, based on 40 % Silica flower which copes with temperatures of 300°C using adequate additives and retarders (4).

A typical high temperature well is shown in Fig. 8 . Here at Latera (7) in a volcano sedimentary context, ENEL utilized a mud based on a sepiolite-bentonite-chromo-lignite formula with XP20 Resinex resin additives and polyacrylates. Other mud formulae used in Italy are (4) : asbestos-fiber muds pretreated with chromo-lignites and non-ionic surfactants; bentonitic muds with FCL/CL stabilized by Synergetic Polymer Blend; bentonitic muds with high ferro-chromo-lignosulfonate/chromo-lignite contents, protected and stabilized by asphaltic oil dispersed products.

It can be seen in Fig. 8 that a significant set of conventional wireline logs were ran down hole. In general high temperature do not cause major problems provided there is adequate cooling. Some logging companies claim temperature tolerance up to 260°C for main tools but these limits were not checked in hole in EC wells. As to bottom hole measurements Ameradas and preferably Kuster mechanical devices modified for high temperature service, are found the most reliable and have been used up to 370°C over several hours. Single shot instruments mounted on thermal shields have proved effective at 400°C and 1.5 hours, (4). Open hole packers have failed after 12 hours operating in a 200°C environment in the Phlegreaen fields. Down hole high temperature hardware is being developed with the support of the EC in the following areas : pressure and temperature gauge (300°C, 500 bars), flowmeter-caliper (240°C, 250 bars), fluid sampler (240°C, 250 bars). Research is also conducted for the design of an in hole optical fiber principle for power and signal transmission. A logging facility with a 4000 m Teflon insulated cable is currently operating in Italy.

In Europe a high enthalpy well is considered commercial for a net productive capacity of 1.5 MW_e. Costs of geothermal wells sunk at depths of 2 000 and 2 500 m average 1.9 and 2.4 million US $ respectively. Slim hole (projected not actual) costs for similar depths amount to 500,000 and 650,000 US $. Environmental constraints may add 30 % to the bill (Campi Flegrei).

According to joint AGIP and ENEL calculations (Ceron, personal communication, 1979) the structure of geothermal mining costs is divided as follows (50 % versus 70 % success ratios in percentage of total mining cost) : surface exploration (1.5/2), deep drilling (77.5/70), reservoir engineering (9.5/14), production engineering (9.5/13), disposal (9/11).

Slim hole wildcatting

New tendancies are shaping in high enthalpy exploration drilling. Slim hole wildcats progressively replace the so called shallow gradient holes utilised in the past for heat flow mapping purposes. These slim holes, drilled essentially on geophysical indices down to depths of 2000 m with a Ø 6" terminal open hole diameter, are shown to be three times cheaper than an ordinary exploratory borehole. They are not designed as production wells and their use is therefore restricted to geological reconnaissance, pressure - temperature measurements and reservoir evaluation. As a result, slim hole wildcatting should enable, (i) to speed up exploration, (ii) to cut down exploration costs, (iii) to calibrate geophysics and derive relevant conceptual models and, therefore, (iv) to reduce speculations. Slim holes are currently being drilled or planned in the near future on the following prospects : Somma Vesuvius (Ottaviano permit, Campania, Italy), Sabattini and Cimini (Northern Latium, Italy) and Mont Dore (Massif Central, France) (8).

Deep drilling case studies

In known and recently discovered fields, deep drilling (below 3000 m) aimed at investigating the entire reservoir sequences, is becoming systematic. This procedure, although it poses severe problems associated with higher temperatures and drilling through successive producing layers, is necessary with respect to optimisation of future production and reservoir management. It is also the best possible substitute of past mining practice of taking the best part of shallower producing horizons.

Two wells drilled recently in Italy defended this concept.

A first one was drilled at Sasso in order to explore the deeper parts and locate the water phase of the long exploited Larderello dry steam system which is presently being produced in the upper carbonate reservoir formations (see log in Fig. 9). Target depths of 4500 m were estimated, based on the following arguments, (i) the presence of a regional, continuous and energic seismic reflector and, (ii) source temperature of 350°C inferred from gas geochemistry which attributed a deep origin to 50 % of the gasses trapped in the upper field. As a whole this project ought to be regarded as a combined exploration and drilling technology research venture.

The second well has just been completed at San Vito, in Campi Flegrei, a pressurized water system developing in an active volcanic context (see map in Fig. 11)(5). Here the objective was to step out of the Mofete block, at present in the evaluation stage, and to investigate the adjacent and lower compartment close to a normal fault trending radially to the Pozzuoli caldera. A depth of 3000 m was assigned to the San Vito hole against 2000 m for the deepest well in Mofete.

The Sasso 22 deep drilling (3)

Two drilling phases can be distinguished, namely :

- first, the crossing of the upper producing reservoirs which ended after one year with the setting and cementing of the Ø 9" 5/8 casing. This phase is dominated by lost circulation (see Fig. 9).

- second, the drilling below 3000 m, in a harsh environment as to rocks and temperatures. It is characterized by lost circulation, tool deviation, drill pipe corrosion, breakage, fishing and side tracking (see Fig. 10). It lasted eleven months.

If phase one could well be regarded as one eyed, phase two was definitely blind. To our knowledge, very few wells, if any, have exhibited so many difficulties and hardware failures at the same time (2).

Starting from 608 m the hole was drilled in total lost circulation using plain water as a drilling fluid with viscous plugs pumped in at each stem move. Lost circulation is caused by large fractures and cavities and cannot be controlled neither by chemical - plugging agents - nor mechanical - bento block - means. Consequently, no return circulation being possible, the cuttings are not recovered and little stiffening is applied to the drilling string. As a matter of fact no stabilizers could be used. Still, tool blocking, stuck drill collars and breakage of bottom hole assemblies were sometimes noticed but remained under control. In particular, the injection of cold water and its subsequent shrinkage proved effective in getting unstuck.

Cementing, with stinger, of the 9" 5/8 casing could not be achieved over the required length, regardless of the often ambiguous indication of the CBL, owing to the presence of several fissured absorbing horizons. So, perforating and squeeze were necessary.

Otherwise, the bit record proved satisfactory with average 50 hours and 95 meters figures and the following wireline logs could be run : HRT - BHC - GR - DLL - BHC - LS - C and flowmeter.

Below the 9" 5/8 casing shoe the presence, in addition to important lost circulations hit at 3000 m, of hard and highly heterogeneous metamorphic rocks - gneisses and amphibolites - caused the deviations and severe dog legs displayed in Fig. 10. In conjunction with high temperatures, corrosion was another puzzle. Breakage of drill pipe often occured and even several ring elements of the annular BOP were found down hole. Frequent fishing jobs took place which, owing to bottom hole temperatures in excess of 350°C, could not call upon explosive and hydraulic (back off, bumper sub, etc) recovery techniques. When fishing failed and deviation drifts showed excessive, side tracking was the rule. Placing of cement plugs, to keep the whipstock stationary, not being possible, short cuts were required to side track without reentering the hole. After a first failure to deviate from the first side track (see Fig. 10), a second whipstock based on a conventional design was manufactured by a service company. After positioning down hole a taper mill opened a one meter long guide hole for the bit. Then, combinations of insert bits and of various bottom hole assemblies enabled to pass the fish and continue drilling until a depth of 4094 m was reached thus establishing a new record in geothermal drilling.

Finally, the persistance of this hostile environment caused the well to be abandoned soon after a third side track had been attempted. The 9" 5/8 casing was in so bad shape after many string manoeuvres and shocks in an empty space (down to 2200 m) that the well had to be plugged. Further analyses of samples of tubulars recovered down hole proved that stress corrosion had been aggravated by the use of steam condensates, from the nearby geothermal power plant, as a drilling fluid.

However, the outcome of this deep drilling venture was not negligible. From a geothermal stand point it proved that a second reservoir was developing down to a depth of 3800 m. Over one million m3 of water were injected which demonstrated the high absorption capacity of the fractured basement rocks. Core analyses led also to a refined scenario of the temperature history of the Tuscan geothermal field. Paragenesis study showed, in particular, a high temperature event associated with anatectic magmatism followed by a recent hydrothermal activity. As far as drilling technology is concerned, the major conclusions can be summarized as follows :

- deviation control is absolutely vital in these environments. In no way are high temperatures an obstacle to standard single shot operating provided the injected water cools down the hole to the required level.

- it is recommended that future jobs in similar conditions make use of non stabilised heavy drill collars (Uranium, Tungsten) to prevent excessive deviations.

- side tracking over 350°C cannot rely on cement plugs, neither on diamond bit which totally failed nor on turbines.

- new specifications as to tubular, well heads, BOP's and particularily seal requirements and inspection are urgently needed for high temperature operation.

- chemical composition and agressivity of injected waters should be carefully tested with respect to stress corrosion.

Incidentally this drilling triggered two research projects, adressing, (i) the design and testing of a mechanical device to beat lost circulation in extensively fractured media and, (ii) the implementation of light weight ($d \leq 1.5$) geothermal cement slurries.

The San Vito Well (1)

This exploratory hole drilled by AGIP, operator of an ENEL-AGIP joint venture, with an IDECO super 711 rig, is a good example of the problems encountered while drilling in a very high temperature volcanic environment, which required two major instrumentations.

Drilling of the upper 2000 meters proved relatively easy as it benefited from the experience acquired while drilling the three previous wells at Mofete (see location in Fig. 11), sunk at similar depths. In particular, it can be noticed from Fig. 12 that a substantial set of wireline logs could be run down to 2200 m, by adequate cooling.

A first fishing job was attempted at a depth of 2330 m (see Fig. 13) to recover the bottom hole assembly. After several unsuccessful trials the fish is abandoned down hole.

The well is then side tracked in the open hole section, just below the 9" 5/8 casing shoe (Fig. 13). Drilling continues down to 2488 m. Here, further to the stopping of circulation, the mud is gelled and coagulates. The release of the assembly is attempted by sending a Ø 1" 1/2 scallop gun down the string to perforate and reestablish circulation. It fails because the high temperatures building up in hole decompose the explosive charge. A second trial with a coiled tubing (Ø 22 mm) also fails.

Again, the bottom hole assembly is left down hole and a back-off is planned in a shallower horizon (2013 m, some 30 m above the 9" 5/8 casing shoe) where lower formation temperature could secure the operation. The job succeeds and the assembly is released but 395 m of Ø 6" 3/4 drill collars remain at bottom hole.

A second side track is completed by milling the 9" 5/8 casing, over a length of 25 m (between 2025 and 2050 m, Fig. 12), utilising a positive displacement motor and a 1° 30" bent sub. After 5 days of operation drilling resumes and progresses down to 2500 m where the 7" slotted liner is set. Drilling continues in Ø 6" to 3045 m (TD). A deviation of 5° is measured, the return mud temperature being stabilised at 100°C.

Bottom hole temperatures were recorded on an Amerada gauge at 2500 m and reached 301°C after 43 hours. At total depth, after one week, BHT could not be measured anymore with standard equipment and a temperature of 419°C was inferred from the melting of a zinc sample.

The well was then killed after a short production test showed rapid increases in temperature at the well head, not rated for temperatures in excess of 300°C. A new well head is being designed to cope with temperatures of 400°C and pressures of 220 bars and also the presence of CO_2. Environmental considerations - the well is drilled in an active volcanic and occasionaly densely populated area - require drastic safety and monitoring regulations before any production test be undertaken. There are also strong expectations that the geothermal fluid is in a supercritical state which has obvious implications on both production and reservoir physics.

Experience gained during drilling can be summarized as follows :

i - mud can be used as a drilling fluid provided it is designed for high temperature usage.

ii - at San Vito, muds contained attapulgite (or sepiolite) suspended in a polymer solution with KCl as a swelling inhibitor in a tuffaceous alkaline rock context.

iii - mud density ought to be increased and kept as close as possible to the 1.15 target, taking into account losses.

iv - keeping the mud below 100°C, and preferably around 90°C, is essential. It is achieved by rapid circulation and by a cooling facility (tower) at surface.

v - lost circulations, after deduction of evaporation losses occuring in the cooling tower, must be carefully monitored and, whenever they exceed the 2 m3/h threshold, a cement plug is to be set down hole.

vi - it is necessary, by all available means, to shorten interruptions of circulation and to carry out partial circulation during manoeuvers.

vii - utilisation of jars, bumper subs and float valves above the tool are strongly recommanded to avoid sticking.

viii - stabilised rotary bottom hole assemblies are necessary.

ix - periodical cleaning of drill pipe is mandatory to optimize circulation.

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Table 1

EC Geothermal Well Record

Geothermal Fields	Number of Wells drilled	Number of Wells productive	Success Ratio %
Temperature above 150°C :			
Italy			
- Larderello (1904-1976)	513	338	66
- Larderello (1976-1978)	66	33	50
- Monte Amiata, Pian Castagnaio	63	38	60
- Travale, Radicondoli	39	20	51
- Torre Alfina, Cesano, Vico, Latera	19	10	53
- Vulcano, Sciacca, Mofete, San Vito	7	5	71
- Viterbo, Campi Flegrei, Ischia (1940-1960)	105	5	5
Greece			
- Milos	2	2	100
Total High Enthalpy	814	451	55
Temperature below 150°C(*) :			
France			
- Paris Basin	18	17	94
- Aquitaine	7	6	86
- Limagne	1	0	0
- Rhine Graben	1	1	100
Germany			
- Rhine Graben	1	0	0
Denmark			
- Danish Basin	1	0	0
Belgium			
- Hainault	2	2	100
Italy			
- Po Valley	1	0	0
United Kingdom			
- Wessex Basin	1	1	100
Total Low Enthalpy	33	27	82
Grand Total	847	478	56

(*) including reinjection wells and wildcats

Table 2

Typical cost figures of a geothermal district heating scheme

Characteristics :

Total depth :	1800 m (2 vertical holes)
Production rate :	125 m3/h
Bottom hole temperature :	94 °C
Heat load :	2000 equivalent dwellings, each 185 m3
Oil savings :	2500 TOE's yearly
Total cost (1981) :	6 million US $

Breakdown of costs :

	Cost (1,000 US $)	%
Drilling	1380	23
Products, services	450	7.5
Power	150	2.5
Tubulars, well heads, primary circuit piping	1140	19
Pumping (production, reinjection, feed)	240	4
Process engineering	360	6
Total subsoil investment	3720	62
Surface equipment(*)	360	6
Piping	1440	24
Consulting fees	480	8
Total	6000	100

Ratios :

Payback time : 13 years
Rate of return : 8.5 %

(*) Titane plate heat exchanger and degassing unit

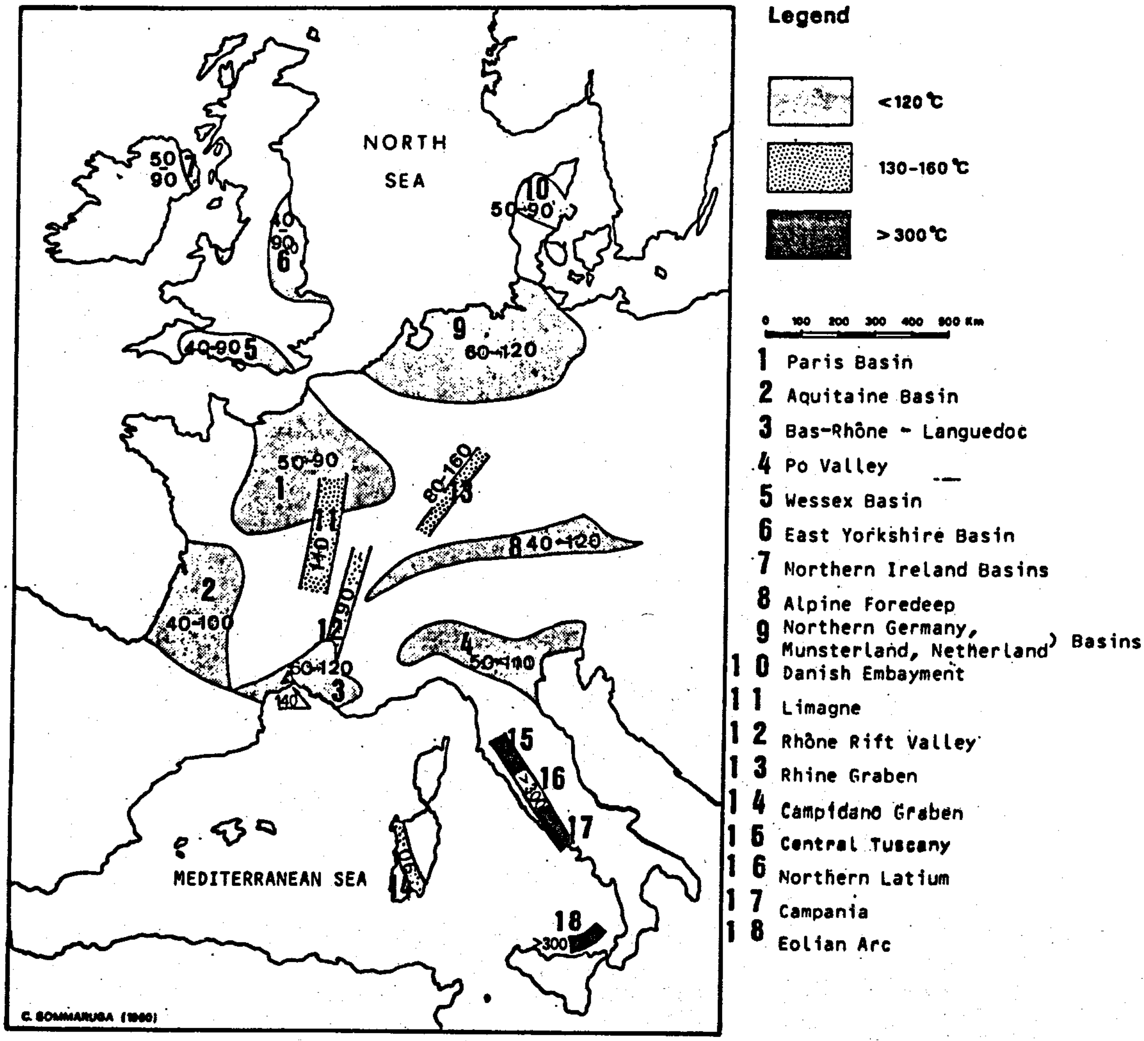


Figure 1 - An outline of EC geothermal resource status.
Reservoir temperature range at depths varying from 1 to 3.5 km
(after Sommaruga and Haenel)

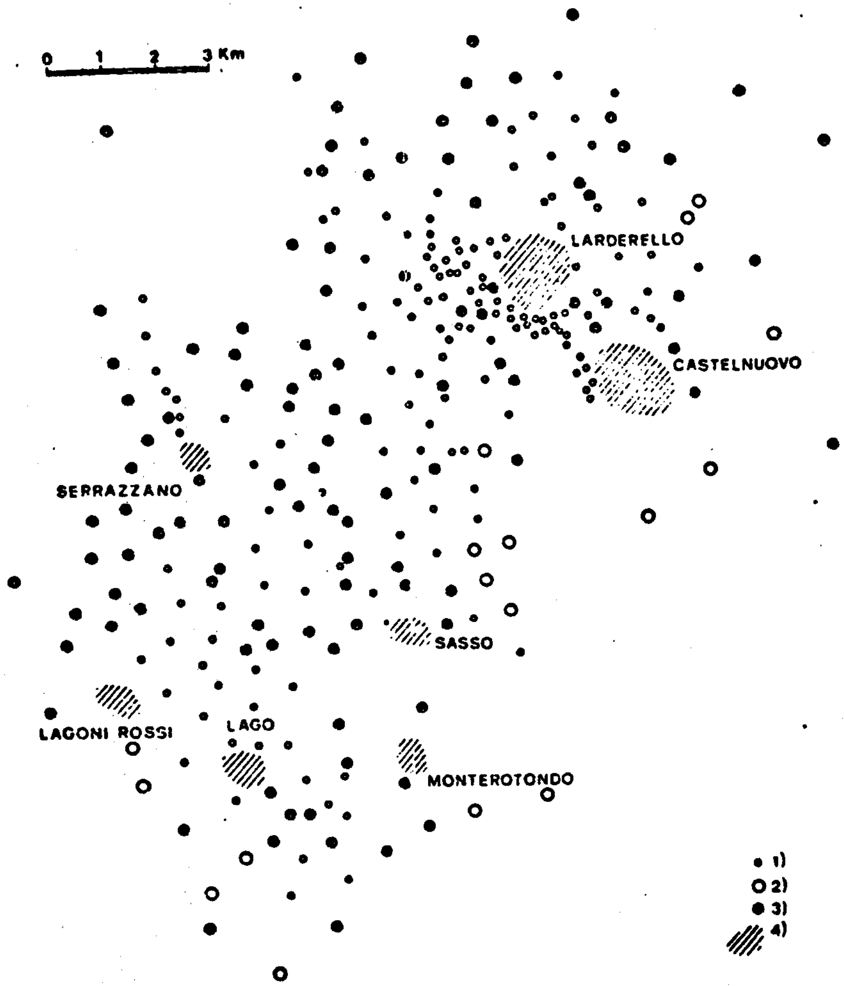
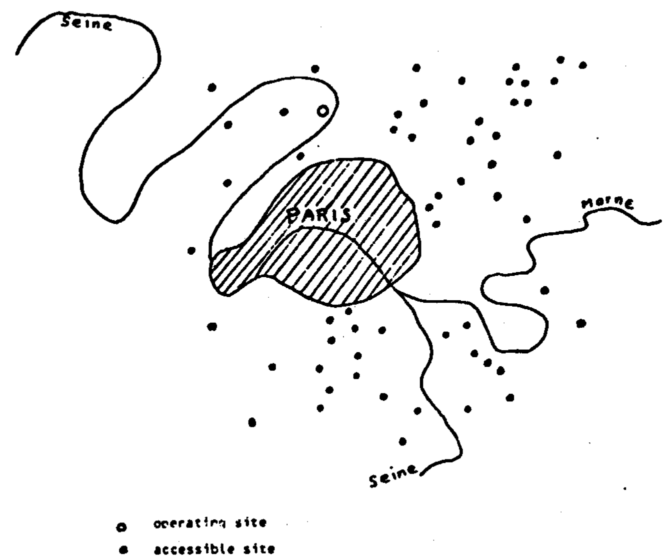


Figure 2 - Larderello field. Well location map (after ENEL)
1) Productive well
2) Non productive well (low temperatures)
3) Dry hole or poor producer
4) Densely drilled area



A total of 60 developable sites represent a heat load of 300 000 TOE's e.g. 200 000 equivalent dwellings each 200 m^3 in volume. The actual potential market represents over 1,000,000 equival. dwellings e.g. 1,500,000 TOE's.

Figure 3 - Geothermal district heating opportunities in the Paris Suburbs (restricted to accessible sites)

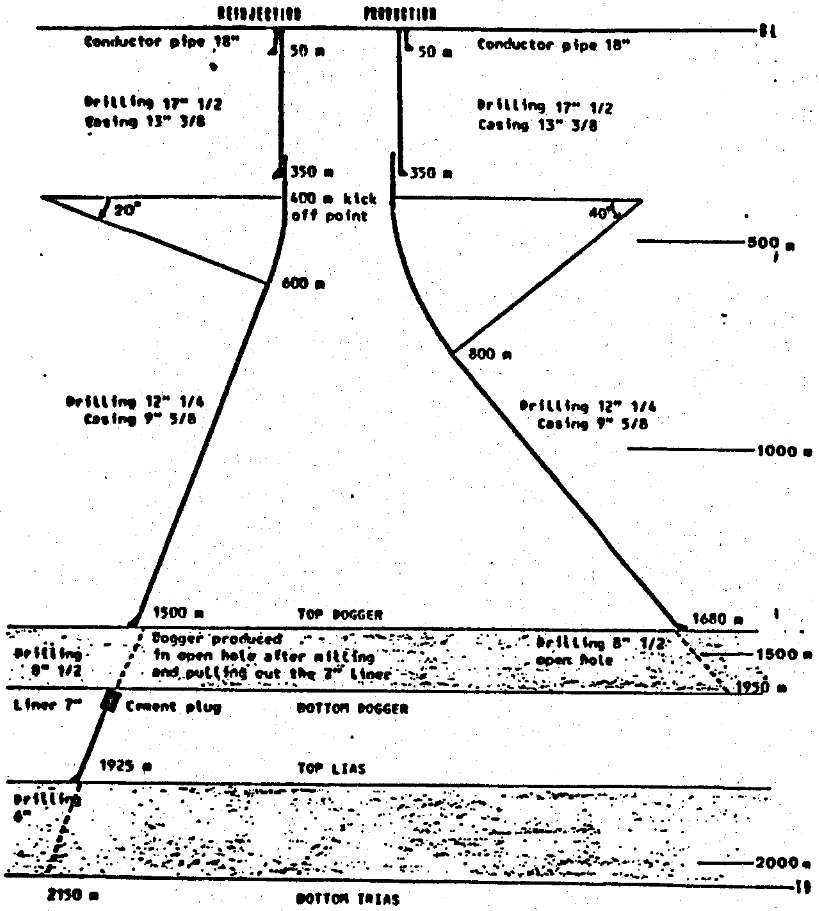


Fig. 4 - Multi aquifer reconnaissance.
Drilling and well design
(after Geoservices Hydrologie)

STAMPIAN	Fontainebleau sands	OLIGOCENE
BARTUNIAN LUTETIAN YPRESIAN	Limestone, marl, sand and clay	EOCENE
SENONIAN	Silex chalk	UPPER CRETACEOUS
TURONIAN	Grey chalk	
CENOMANIAN	Marly chalk	
ALBIAN	Clay and sand	LOWER CRETACEOUS
APTIAN BARREMIAN NEOCOMIAN	Black clay Variegated sandstone clay	
PURBECKIAN PORTLANDIAN KIMMERIDGIAN	Alternating limestone marls and sandstone	MALM
LUSITANIAN	Limey serie with interbedded marl	
OXFORDIAN	Black marl	
CALLOVIAN BATHONIAN BAJOCIAN AALENIAN	Marls. Oolitic reference Gravelly and oolitic limestone Zoogenic marl	DOGGER
TOARCIAN PLIENSBACHIEN	Black pyritic marl	LIAS
SINEMURIAN HETTANGIAN	Alternating marl and dolomite	
RHETIC KEUPER	Clayey sandstone Fine grained sandstone and conglomerate	TRIAS
BASEMENT	Schist	PALEOZOIC

Fig. 5 - Synthetic lithostratigraphic log in the centre of the Paris Basin

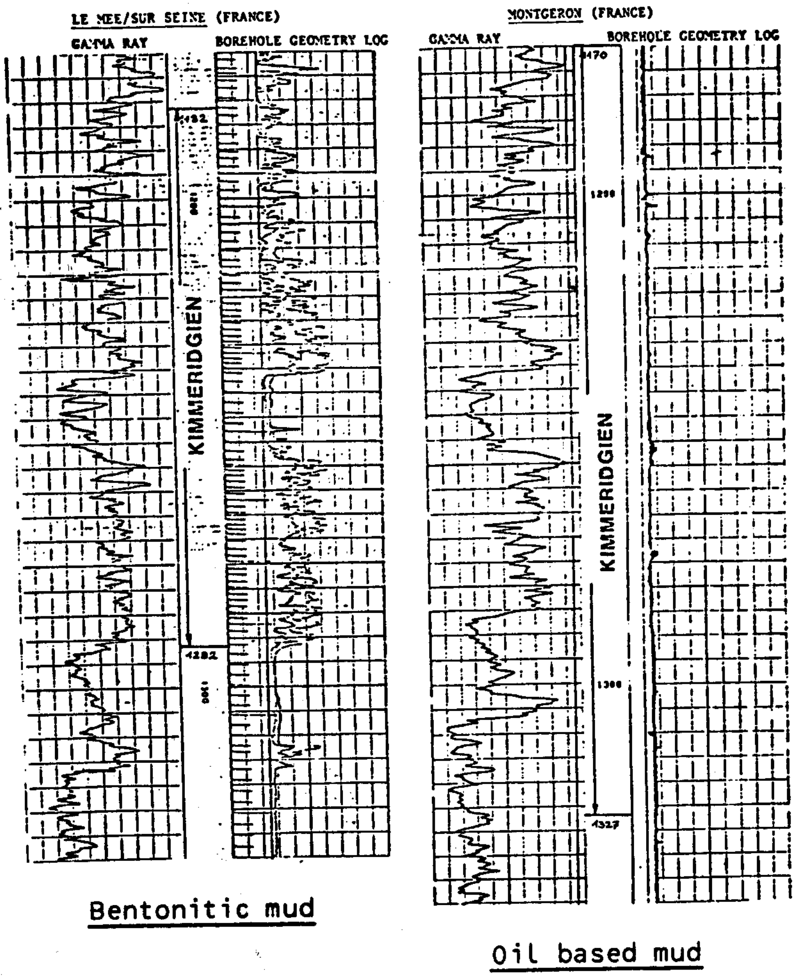


Fig. 6 - Borehole geometry. Comparison between two geothermal well bores drilled with a conventional bentonitic and oil based muds (after Geoservices Hydrologie)

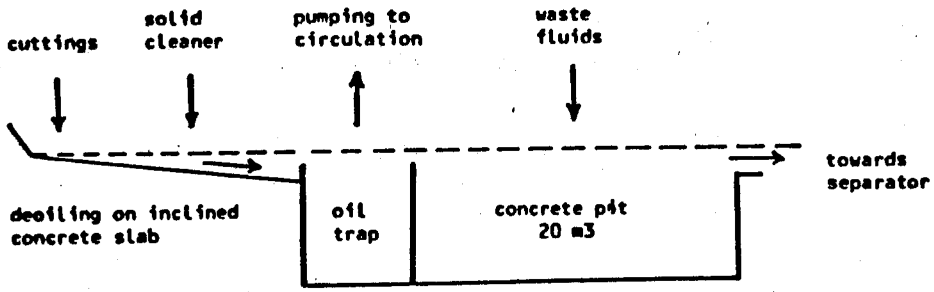


Fig. 7 - Simplified mud circuit (after Vathaire et al)

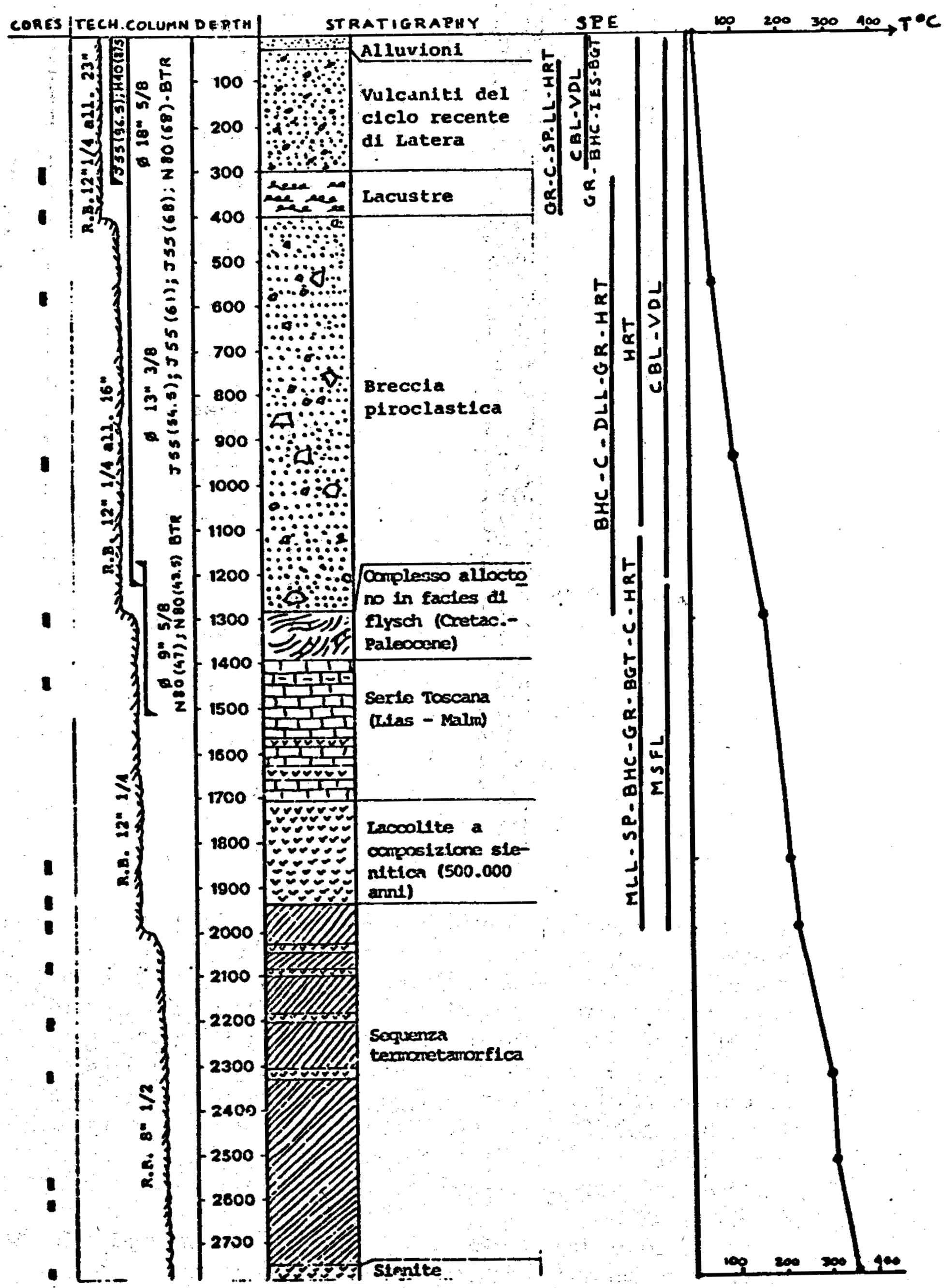
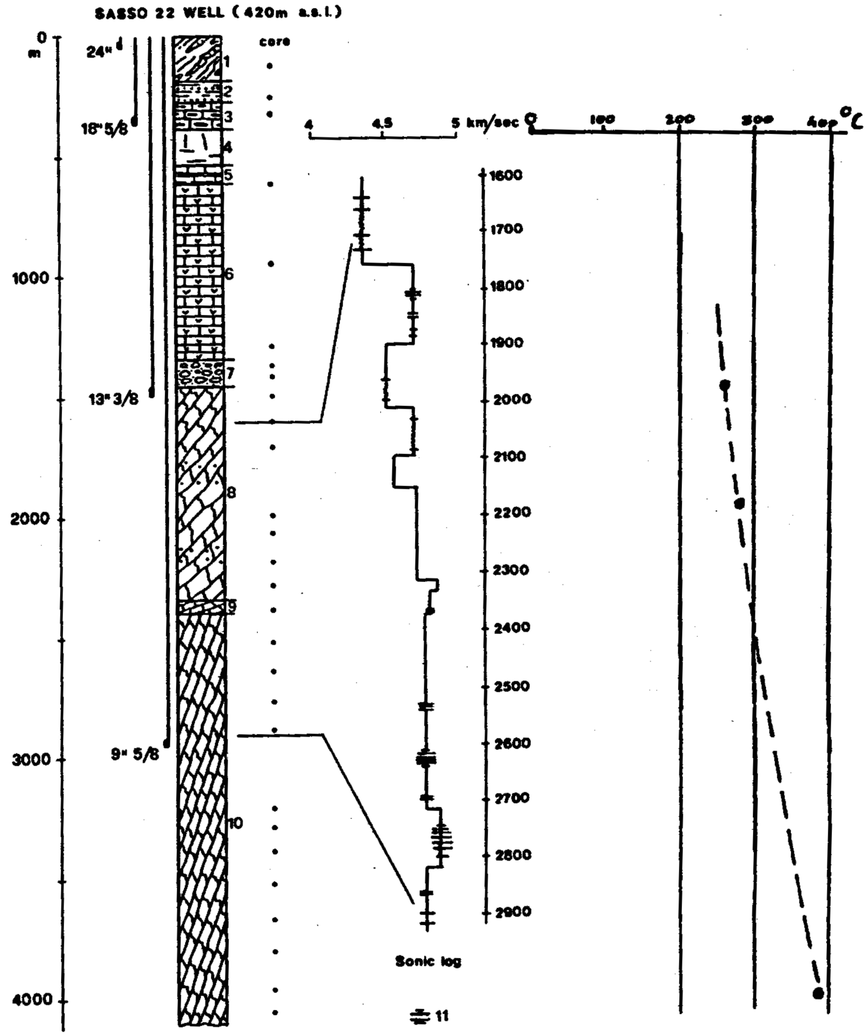


Fig. 8 - Latera Well logs (after ENEL)



1) Eocenic Ligurian Nappe:flysch sequence of shaley and sandy sediments. 2)Oligocenic sandstone('macigno').3)Stratified cherty limestone.4)Massive limestone. 5)Marly dolostone. 6)Carbonate and anhydrite (Burano Formation). 3) to 6) are of Mesozoic age. 2)to 6) belong to the Tuscan Nappe. 7) Triassic slightly metamorphic quartz pebble conglomerate and coarse quartz-arenite (basal levels of the Tuscan Verrucano). 8)Quartzite,phyllite,metagreywacke,metabasite of Lower Paleozoic'Filladi inferiori'Group. 9)Garnet-bearing plagioclase micaschist (Lower Paleozoic-Pre-Cambrian?). 10)Fine-grained gneisses and thin interbedded amphibolite levels (Lower Paleozoic-Pre-Cambrian?).
Processed sonic log on the right refers to the interval 1600-2900 m of the basement. 11) Higher permeability horizons.

Fig. 9 - Well Sasso 22. Lithostratigraphic, sonic and temperature logs (after ENEL)

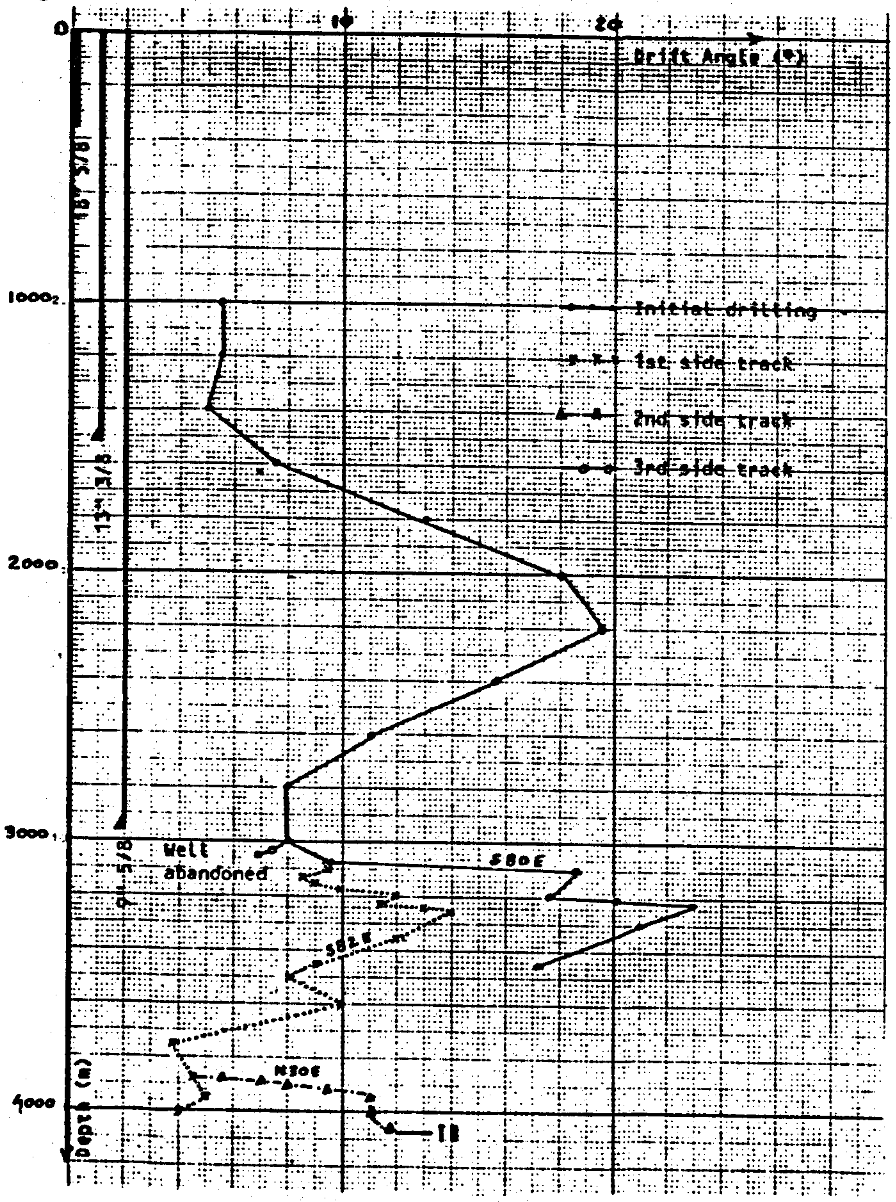


Fig. 10 - Sasso 22 Well. Verticality log

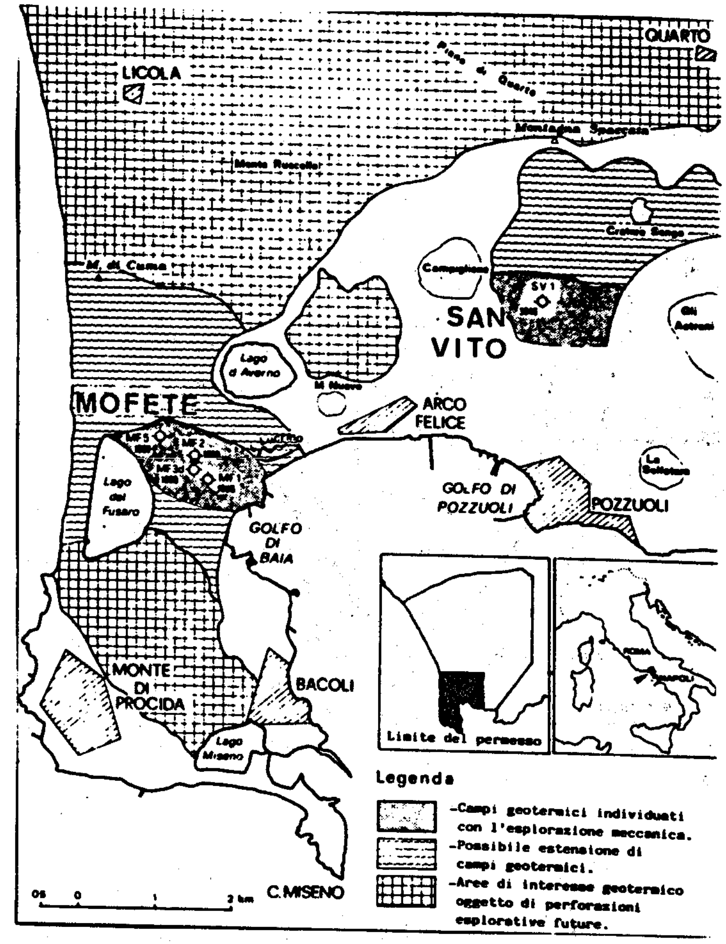


Fig. 11 - Phlegreaen Fields. Location map

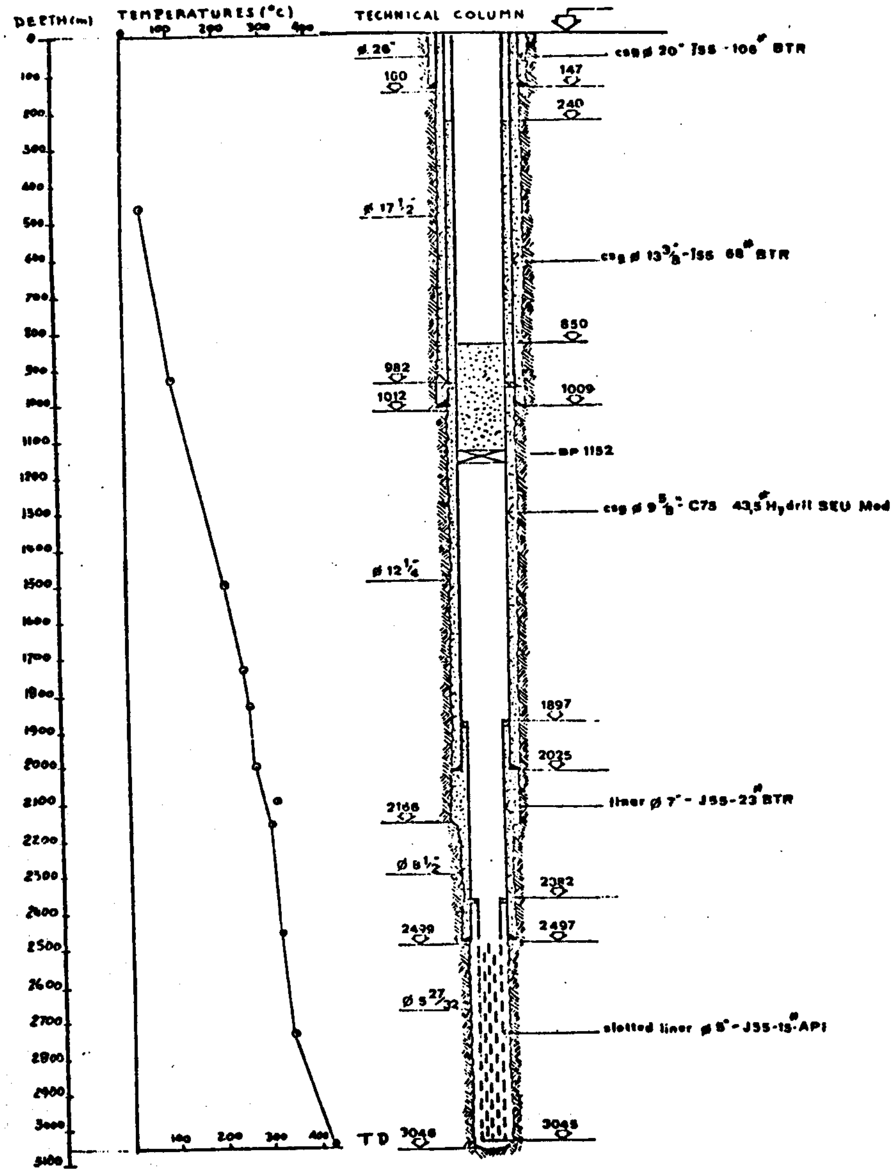


Fig. 12 - San Vito well logs (after AGIP)

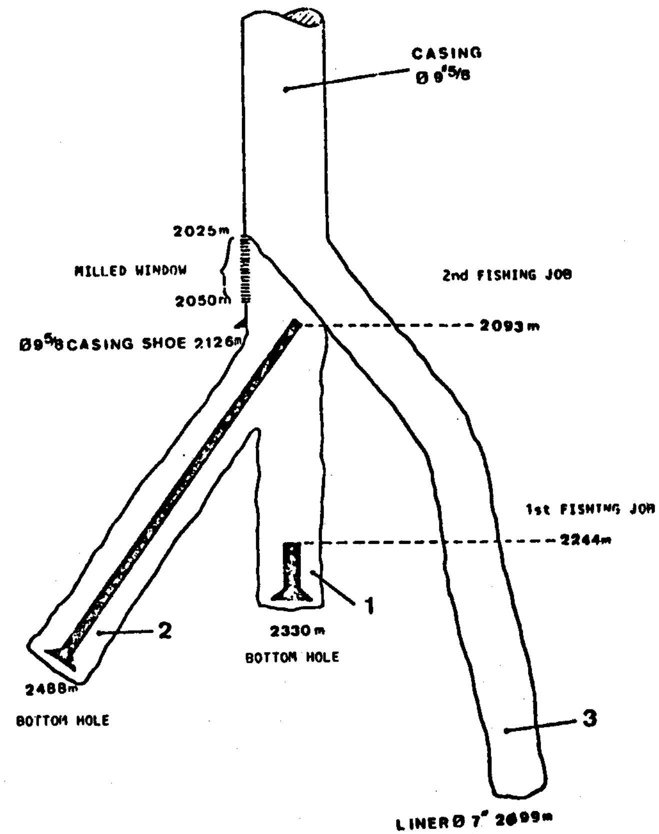


Fig. 13 - San Vito well. Side tracks (after AGIP)